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# Hall Effect Spintronics

**Alexander Gerber**

**Tel Aviv University**
**Research Authority**
**School of Physics and Astronomy**
**Tel Aviv, 69978 Israel**

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**14. ABSTRACT**

The grant research covered a wide variety of Hall effect topics. First, a non-switching van der Pauw technique was developed using two electrically isolated AC sources with two frequencies and averaging two sets of simultaneous data, which reduces the effect of parasitic offset voltage for more accurate measurements of the Hall effect. Second, investigation of asymmetric in-field magnetoresistance was investigated in seeming violation of Onsager's reciprocity relations, with the conclusion that variations in thickness, Hall coefficient, and nonuniform magnetization reversal can explain the phenomena. Third, thin Co/Pd multilayers with room temperature perpendicular anisotropy and enhanced surface scattering were examined for possible use in extraordinary Hall effect (EHE)-based memory devices, and several parameters important for EHE-based devices were found promising. Fourth, a novel technique was developed to monitor magnetization reversal and perpendicular anisotropy using the extraordinary Hall effect and anisotropic magnetoresistance, finding that canted fields at certain angles can significantly improve measurements of anisotropy. Fifth, the response of magnetization to an unpolarized current is examined, proposing a mechanism which acts in the bulk of the ferromagnet rather than the interface between normal and ferromagnetic layers, and a study was performed on the effects of temperature and current density on magnetization reversal of thin Ni films, showing evidence of destabilization of magnetization by unpolarized electric current. Sixth, a method was developed for realizing two-bit-per-ferromagnetic-dot magnetic random access memory using magnetic vortex states, in which two states are contributed by clockwise and counter-clockwise chirality and two by up/down core polarity. Seventh, the dynamics of magnetization reversal in ferromagnetic films with perpendicular anisotropy were examined, and finally, the magnetoresistance and Hall effect in Manganese-doped Germanium was examined, finding huge positive magnetoresistance and a non-monotonic sign-reversing field dependence of the Hall effect. Ten publications arising from this grant are listed.

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# Hall Effect Spintronics


Alexander Gerber

School of Physics and Astronomy,

Tel Aviv University,

Ramat Aviv 69978, Tel Aviv, Israel.

This document presents a brief account of progress and achievements in research and development of the extraordinary Hall effect – based spintronics accomplished in the framework of Department of Defense - DOD, U.S. AIR FORCE Grant No. FA8655-11-1-3081.

**1. Development of a non-switching van der Pauw technique to improve the accuracy of the Hall effect measurements.**

Under ideal conditions the Hall voltage is antisymmetric in external magnetic field and crosses zero at zero field. In real samples one usually finds a finite zero field offset voltage, which can be significantly larger than the Hall effect signal. This undesired offset can be a consequence of geometrical mismatch in voltage contacts, misalignment of the magnetic field and current directions, inhomogeneity of the sample, temperature gradients or piezoresistive effects. As an additional complication, the offset voltage can change in time due to e.g. the sample's ageing or instability of temperature conditions. We developed a novel non-switching van der Pauw technique for measurements of the Hall effect. Experimental setup uses two electrically isolated alternating current sources operating at two different frequencies and two lock-in amplifiers. Parasitic offset voltage is reduced by averaging two sets of data accumulated simultaneously. Application of the technique is particularly useful when the offset changes on a time scale comparable to the measurement cycle. In industrial applications this technique can be used as a relatively simple design for offset reduction over a long period of operation.

The work has been published in:

O. Riss, E. Shaked, M. Karpovsky, and A. Gerber

*Offset reduction in Hall effect measurements using a nonswitching van der Pauw technique*

Rev. Scientific Instruments 79, 073901 (2008).

## 2. Asymmetric field dependence of magnetoresistance in magnetic films.

Onsager's reciprocity relations are the cornerstone in understanding the field symmetry of magnetotransport measurements. Magnetoresistance or longitudinal resistivity (measured along the current flow direction) is predicted to be an even function of magnetic induction B, while transverse (Hall) resistivity is specified to be odd with respect to B when a magnetic field is applied perpendicular to the sample plane. General acceptance of these rules is so common that in numerous experimental cases, when current and voltage contacts can not be arranged in a well defined 5-probe geometry, the magnetoresistance and Hall effect data are respectively extracted as the even and odd in field components of the measured 4-probe signal. However, asymmetric in field magnetoresistance is quite frequently observed in magnetic materials (also in samples with fully symmetric magnetic properties and properly arranged current and voltage contacts), although this is rarely mentioned and discussed. A seeming violation of Onsager's law only recently attracted attention when sharp distinctive peaks of magnetoresistance, odd with respect to applied field, were found at magnetization reversal of ferromagnets with an out-of plane magnetic anisotropy. As argued by Cheng et al the effect can appear when a domain wall (DW), located between the voltage probes, runs perpendicular to both magnetization and current. Electric fields generated by the extraordinary Hall effect (EHE) have opposite polarities on both sides of the DW, which can produce a circulating current loop and a respective extra voltage contribution. The model was used to explain the odd in field longitudinal voltage peaks in a specially designed Co-Pt multilayer film with a single DW gradually propagating along the sample. However, the effect was also observed in other samples with multiple domains, and the applicability of the "single wall" model in this general case is dubious.

We studied the asymmetric field dependence of magnetoresistance in several magnetic films, in particular in ferromagnetic CoPd ferromagnetic films with perpendicular magnetic anisotropy. We reached a conclusion that minor variation of thickness, Hall coefficient and non-uniform magnetization reversal along the sample can explain the anomalous phenomena. We have shown that a non-uniform variation of the Hall voltage along the sample generates an additional odd in field longitudinal voltage signal proportional to the field derivative of the transverse voltage. This additional signal can be significant when the Hall voltage varies sharply with the applied field, like in the case of magnetization reversal in films with perpendicular magnetic anisotropy, studied here, at superconducting transitions or in materials demonstrating the quantum Hall effect. The fingerprint of the mechanism is the reversal of the asymmetry when the longitudinal voltage is measured along the opposite edge of the sample.

This work has been published in:
A. Segal, O. Shaya, M. Karpovski and A. Gerber
Assymetric field dependence of magnetoresistance in magnetic films.
Phys. Rev. B 79, 144434 (2009)

**3. Preparation and study of CoPd multilayers for the Extraordinary Hall Effect based magnetic memory.**

Thin Co/Pd multilayers, with room temperature perpendicular anisotropy and an enhanced surface scattering, were studied for the possible use in the extraordinary Hall effect (EHE) - based magnetic memory devices. Several parameters important for the room temperature applications of the EHE-based memory devices were found promising: EHE resistivity is of the order of 0.5 $\mu\Omega cm$, which is equivalent to a difference of the order of 1Ω between the up- and down- magnetized states; coercive field depends linearly on a number of bilayers and can be tailored in the field range of 10 - 1000 Gauss. Polarity of the EHE signal was found to depend on thickness and time elapsed since the deposition. We argue that the effect is determined by surface scattering in thin and aged samples. It would be beneficial to find a proper matching in polarity of spin-orbital scattering within and at the surface of the selected material, while in Co/Pd multilayers studied here these polarities are opposite.

The work has been published in:
D. Rosenblatt, M. Karpovski and A. Gerber

*Reversal of the Extraordinary Hall Effect polarity in thin Co-Pd multilayers*.
Appl. Phys. Lett., 96, 022512 (2010).

**4. Monitoring magnetization reversal and perpendicular anisotropy by the extraordinary Hall effect and anisotropic magnetoresistance.**

Ferromagnetic films with perpendicular magnetic anisotropy attract significant attention as strong candidates for realizing ultra-high density recording systems. For this, detailed information on the magnetization reversal mechanisms and determination of the magnetic anisotropy constants are particularly important. The magnetic anisotropy constants can be extracted from measurements of the out-of-plane component of magnetization by using the Stoner-Wohlfarth model. The model is applicable for rotation of a single magnetic moment vector and is limited to the range of fields and angles at which rotation of magnetization is coherent in the entire sample.

We developed a novel technique by using two magnetotransport properties of ferromagnetic materials: the extraordinary Hall effect and anisotropic magnetoresistance to monitor the normal and in-plane projections of the magnetization in thin Co/Pd multilayers with perpendicular anisotropy. By reconstructing the normalized magnetization vector we were able to distinguish between the coherent rotation and domain nucleations during the process of magnetization reversal. Two experimental protocols were used: the traditional one which involves rotation of a magnetized sample and measurements in fields applied parallel to the film plane, and a new one, in which the entire experiment is performed under canted fields applied in a fixed orientation. We found that under fields canted beyond a certain critical angle the complete cycle of magnetization reversal takes place by a coherent rotation with an intermediate sharp flip-flop of the out-of-plane component. The range of applicability of the Stoner-Wohlfarth model is extended, and thus reliability of the extracted anisotropy constants is significantly improved when the measurements are performed under canted fields.

The work has been published in:

D. Rosenblatt, M. Karpovski and A. Gerber

*Monitoring magnetization reversal and perpendicular anisotropy of ferromagnetic films by the extraordinary Hall effect and anisotropic magnetoresistance.*
Jour. Appl. Phys. 108, 043924 (2010).

**5. Search for non-thermal magnetization reversal assisted by unpolarized current.**

Interplay between the spatial distribution of magnetic moments and electric current is the essence of the science of spintronics. Giant magnetoresistance (GMR) can be thought as the response of the current to a gradient of magnetization. The opposite effect: response of the magnetization to an electric current is now under scrutiny. Ferromagnets serve as spin filters for an electric current passing through the magnet: spin of the electrons that are transmitted through a ferromagnet becomes partially polarized parallel or antiparallel to the direction of the magnetization, whereas spin current perpendicular to the magnetization direction is absorbed. Spin filtering is the root cause for the spin-transfer torque, the phenomenon in which a polarized current impinging on a ferromagnet affects its magnetization direction. The spin-transfer torque gives rise to magnetization reversal and excitation of spin-waves in ferromagnet/normal-metal/ferromagnet trilayers (F/N/F) and domain wall motion in bulk ferromagnets and wires.

The original models of current induced spin wave excitation rely on exchange model of interaction between the itinerant electrons and the localized spins. It has been recently reported by I.Ya.Korenblit that in ferromagnetic conductors with large extraordinary Hall effect the relativistic electromagnetic interaction of the electron current with the field of the spin-wave can lead to current-induced spin-wave instability at critical *unpolarized* current of the same order or even smaller than that in the exchange interaction models. Unlike the exchange coupling of itinerant electrons with the spin-waves, which is effective only in the vicinity of the interface between normal and ferromagnetic layers, the above relativistic interaction acts also in the bulk of the ferromagnet. The mechanism proposed can be relevant for ferromagnetic films with an enhanced extraordinary Hall effect, like thin films of itinerant ferromagnets. In films with an out-of-plane magnetic anisotropy and magnetic moment oriented perpendicular to current direction the critical current of the instability is predicted to be in the range of $10^5$ – $10^7$

A/cm$^2$ which is much smaller than the critical current for spin-wave excitation with spin-transfer torques.

In this work we performed a systematic study of effects of temperature and current density on magnetization reversal of thin Ni films in a search of mechanisms not related to spin polarization and Joule heating by passing current. Although heating is obviously present at high current densities, we identified a number of features inconsistent with the "thermal-only" mechanism: (i) the dependence of effective magnetic temperature on current density is significantly different from the known in art; (ii) the critical current density, beyond which the coercive field starts being dependent on current, increases with temperature despite of deterioration of cooling conditions; (iii) high enough current density was found to reduce the coercive field but not the value of the temperature dependent magnetization. The complex of these properties can be considered as an evidence of destabilization of magnetization by unpolarized electric current.

The work has been published in:

O.Riss, A.Gerber, I.Ya.Korenblit, M.Karpovsky, S. Hacohen-Gourgy, A.Tsukernik, J.Tuaillon-Combes, P. Melinon, and A.Perez

*Non-thermal magnetization reversal assisted by unpolarized current.*

Phys. Rev. B 82, 144417 (2010).

**6. Exploration of Hall effect in ferromagnetic dots in magnetic vortex state.**

Ferromagnetic dots exhibiting a magnetic vortex state are considered to be competitive candidates for the next generation of memory cells due to low stray field affecting neighboring cells and short writing times. Distribution of magnetization in the vortex state consists of an in-plane circular magnetic structure with either clockwise (CW) or counter-clockwise (CCW) chirality, and an out of plane magnetized core directed either up or down. Chirality and polarity are independent parameters that a priori could be used for realization of two-bit per dot magnetic memory in which two states are contributed by clockwise and counter-clockwise chirality and two by up and down core polarity. In this work we made numerical calculations of the vortex core contribution to magnetotransport properties of the vortex state in ferromagnetic dots. The extraordinary Hall effect generated in the core region has a different field symmetry compared to contributions of anisotropic magnetoresistance and the planar Hall effect which can be used to detect chirality and polarity of the vortex. We developed a method for realization of two-bit per dot magnetic random access memory in which two states are contributed by clockwise and counter-clockwise chirality, and two by up and down core polarity. Dependence of the signal on vortex location, core diameter and other parameters has been studied. We have shown that measurable signals can be obtained in ferromagnetic dots with perpendicular magnetic anisotropy and large extraordinary Hall resistivity.

This work has been published in
A. Segal and A. Gerber
Core contribution to magnetotransport of ferromagnetic dots in vortex state
Journal of Applied Physics 111, 073902 (2012)

**7. Dynamics of magnetization reversal in ferromagnetic films with perpendicular anisotropy.**

Reproducibility of cycling processes under identical external conditions attracts particular attention in studies of magnetic hysteresis for at least two reasons: the effect is fundamental to all magnetic storage technologies, and it can serve as a model for a wide range of type-I phase transitions. Two types of hysteresis loops are distinguished. “Major” loops are obtained by sweeping the applied field beyond the saturation field $H_{sat}$, above which the system is said to be fully saturated and its magnetization $M(H)$ is a single-valued function of the applied field $H$; “minor” loops are obtained when the cycle is limited to fields near and below $H_{sat}$. Many studies were devoted to the macroscopic and microscopic repeatability of minor and major hysteresis loops and effects of disorder on cycle-to-cycle memory. Macroscopically the major loops repeat themselves in successive cycles, however it was appreciated that disorder induces memory in the microscopic magnetic domain configurations from one cycle of the hysteresis loop to the next, even when $H_{sat}$ was crossed. Successive minor loops are usually reasonably reproducible, although changes of size and shape were observed. Nevertheless these finite perturbations did not undermine a generally accepted view that macroscopic hysteresis loops are repeatable. It came therefore as a surprise when major cumulative expansion of successive minor hysteresis loops were reported in Co/Pt and Co/Pd multilayers.

We studied the successive minor hysteresis loops as a repetition of fixed field magnetization reversal processes at both field polarities. This simplified case allows understanding the phenomenon of cumulative growth of minor hysteresis loops within the context of magnetization reversal under constant fields - as succession of relaxations and remagnetizations. Successive hysteresis loops were found to evolve according to changes in effective upward $\tau_{\uparrow}$ and downward $\tau_{\downarrow}$ reversal times which depend on population of nucleation sites ready at the onset of each process. Hysteresis loops stabilize and become macroscopically reproducible when $\tau_{\uparrow}$ and $\tau_{\downarrow}$ stabilize. In the case of symmetric-in-field minor loops, stabilization occurs at $\tau_{\uparrow} = \tau_{\downarrow}$. The process can be understood in the framework of a two-directional Swiss-cheese model, in which nucleation sites are generated as small enclaves of non-reversed magnetization left behind the front of propagating domains in both magnetization polarities, regardless of the initial state.

The results of this work are relevant for optimization of non-volatile magnetic memory. Three criteria are important for these applications: stability and magnitude of the remnant magnetic moment, the magnitude of magnetic field required to reverse magnetization to an opposite stable state in the writing process, and the time required for this reversal. For an accelerated writing and power economy it appears advantageous to terminate the reversal in a non-saturated state when the remnant magnetization is very close to the full saturation value, however abundance of non-reversed enclaves ensures a rapid remagnetization to an opposite state.

Part of this work has been published in:
Y. W. Windsor, A. Gerber and M. Karpovski
Dynamics of Successive Minor Hysteresis Loops
Physical Review B **85**, 064409 (2012).

We extended the research of magnetization reversal dynamics to study the effect of small domains, diluted within an oppositely magnetized film, on the rate and character of magnetization reversal in Co/Pd multilayers with perpendicular magnetic anisotropy. These enclaves are remnants of shrinking domains that survive for a long time due to the stabilizing dipolar field generated by the surrounding material. The true saturation field required to eliminate the remnant enclaves and fully magnetize an entire sample in the time scale of a typical experiment is an order of magnitude higher than the observed hysteresis closure field, and thus significantly higher than the values indicated by macroscopic magnetometric measurements. Non-reversed domains serve as ready nuclei for remagnetization and, although their volume is negligible, their presence at the onset of the process can speed up the reversal by orders of magnitude. The effect may be significant for speed and power consumption of technological applications. Finally, we modified Fatuzzo-Labrune model to describe magnetization reversal starting with finite number of pre-existing nucleation domains. Although demonstrated for magnetization reversal in a magnetic material with an anisotropy energy barrier, the model can be adapted to other type I phase and state transitions.

This work has been published in:
Y. W. Windsor, A. Gerber, I. Ya. Korenblit, and M. Karpovski
Time dependence of magnetization reversal when beginning with pre-existing nucleation sites
J. Appl. Phys. **113**, 223902 (2013)

## 8. Hall effect and magnetoresistance in MnGe dilute magnetic semiconductors

Development of spintronics and prospects to reinforce the semiconducting electronics by the spin-dependent degree of freedom has triggered the recent interest in ferromagnetic semiconductors. Germanium doped with Mn is particularly interesting since ferromagnetism in this system is predicted to develop at high temperatures and the material is fully compatible with the existing silicon technology. GeMn films are usually fabricated by molecular beam epitaxial codeposition of Ge and Mn on Ge or GaAs substrates, or by Mn implantation of Ge wafers with or without post-fabrication annealing. Due to the very low solubility limit of Mn in germanium Mn segregation is unavoidable, and doped films are strongly inhomogeneous with $Ge_xMn_y$, metallic precipitates coexisting with Mn-rich regions and Mn dilute matrix. Despite variations among samples grown by different technologies a number of common magnetotransport effects were reported. The most striking of them are a huge positive magnetoresistance, reaching thousands of percent, and a non-monotonic, sign reversing field dependence of Hall effect.

We studied magnetoresistance and Hall effect in Mn implanted Ge samples in fields up to 60 T and analysed the results in the framework of a two- carriers model. Our main findings can be briefly summarized as following: the zero field resistance and the non-monotonic field dependent Hall effect in Mn implanted Ge can be consistently explained by parallel conductance along thick p-type Ge substrate with low concentration of highly mobile carriers and along thin Mn doped Ge layer with low mobility carriers. The same model is not sufficient to reproduce the observed suppression of quadratic field dependent magnetoresistance at low fields and absence of saturation at high fields. Two additional mechanisms have been identified: a strong quasi-linear magnetoresistance of Ge substrate that dominates the low field range and a non-saturating "3/2" power law magnetoresistance of the Mn doped Ge layer dominating the high field range. Comprehensive understanding of both phenomena is lacking. Magnetoresistance due to parallel conductance along two layers is mostly important when resistance of the high mobility layer is lower than that of the low mobility one, while the magnitude of the effect depends on the ratio between resistances of the two layers. New type of sensitive magnetic field sensors using tailored two-layer conductive structures can thus be anticipated.

The manuscript: “Components of strong magnetoresistance in Mn implanted Ge” has been submitted for publication in Journal of Applied Physics.

**Publications emanated from the project.**


1. A. Gerber and O. Riss
*Perspective of spintronics applications based on the Extraordinary Hall Effect.*
(Invited review)
Jour. Nanoelectronics and Optoelectronics 3, 35 (2008).

2. O. Riss, E. Shaked, M. Karpovsky, and A. Gerber
*Offset reduction in Hall effect measurements using a non-switching Van der Pauw technique*.
Rev. Scientific Instruments 79, 073901 (2008).

3. A. Segal, O. Shaya, M. Karpovski and A. Gerber
*Assymetric field dependence of magnetoresistance in magnetic films.*
Phys. Rev. B 79, 144434 (2009)

4. D. Rosenblatt, M. Karpovski and A. Gerber
*Reversal of the Extraordinary Hall Effect polarity in thin Co-Pd multilayers*.
Appl. Phys. Lett., 96, 022512 (2010).

5. D. Rosenblatt, M. Karpovski and A. Gerber
*Monitoring magnetization reversal and perpendicular anisotropy of ferromagnetic films by the extraordinary Hall effect and anisotropic magnetoresistance.*
Jour. Appl. Phys. 108, 043924 (2010).

6. O.Riss, A.Gerber, I.Ya.Korenblit, M.Karpovsky, S. Hacohen-Gourgy, A.Tsukernik, J.Tuaillon-Combes, P. Melinon, and A.Perez
*Non-thermal magnetization reversal assisted by unpolarized current.*
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7. A. Segal and A. Gerber
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8. Y. W. Windsor, A. Gerber and M. Karpovski
*Dynamics of Successive Minor Hysteresis Loops*
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9. Y. W. Windsor, A. Gerber, I. Ya. Korenblit, and M. Karpovski
*Time dependence of magnetization reversal when beginning with pre-existing nucleation sites*
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10. A. Simons, A. Gerber et al
*Components of strong magnetoresistance in Mn implanted Ge*
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